Table 1. The quantities of hydrogen, krypton and carbon available in the world for dilution

	Total (1)	Assumed to be available for dilution
Hydrogen in:		
oceans	1.6×10^{23}g	1.6×10^{22}g
lakes and rivers	5.5×10^{19}g	5.5×10^{19}g
ice	2.4×10^{21}g	...
atmosphere	1.4×10^{18}g	1.4×10^{18}g
sediments	2.2×10^{22}g	...
organic material	4.0×10^{18}g	7.0×10^{16}g
total		1.6×10^{22}g
Krypton:		
volume of the atmosphere (at 0°C, 760 mm)	4.3×10^{24}cc	...
g of krypton per cc of air	4.3×10^{-9}g/cc	...
krypton in the atmosphere	1.8×10^{16}g	1.8×10^{16}g
Carbon in:		
troposphere	5.5×10^{17}g	5.5×10^{17}g
oceans	4.0×10^{19}g	4.0×10^{18}g
lakes and rivers	3.2×10^{17}g	3.2×10^{17}g
land organisms	1.0×10^{17}g	1.0×10^{17}g
sea organisms	8.0×10^{16}g	8.0×10^{15}g
undecayed organic matter	3.9×10^{18}g	...
coal, oil, tar, gas	7.4×10^{18}g	...
total		5.0×10^{18}g

replacement rate which will just maintain the world environment at the limiting specific activity. These annual replacement rates are given in row 12 of Table 2.

The figures in the last three rows of Table 2 are not suitable limits for two reasons. First, these figures make no allowance for the differences between the calculated predictions for an average individual in the population, and the actual exposure received by any particular individual. The Federal Radiation Council and the U.S. Atomic Energy Commission have both stipulated a factor of 1/3 for this purpose. (4, 2)

The second reason why the world capacity figures in Table 2 are not suitable limits is that they make no allowance for the summing of the doses from the three radioisotopes, from all other man-made radioisotopes in the environment, or from other man-made sources of radiation. The intent is that **"persons in the general population at any age. . . should not receive an exposure exceeding 0.5 rem per year in addition to natural background and medical exposures."** (5) In order to allow for the summing of doses from various radioisotopes and other sources of radiation a factor of 1/10 is appropriate.

ALLOCATION

In considering the long pull, one must face the matter of allocation: to how much of the world's capacity is each geographical unit

Table 2. Bases for the calculation of annual replacement rates

	Units	H-3	Kr-85	C-14
1. radioactive half life	years	12.3	10.4	5,600
2. max. perm. body burden (3)	μCi	100	...	30
3. MPC* in public air (2)	μCi/cc	2×10^{-7}	3×10^{-7}	1×10^{-6}
4. MPC* in drinking water (2)	μCi/cc	3×10^{-3}	...	8×10^{-4}
5. max. daily intake in water (2)	μCi/day	7	...	2
Specific activitylimit set by:**				
6. breathing	μCi/g	0.6	70	1
7. drinking water	μCi/g	0.3	...	1
8. eating food	μCi/g	0.2	...	0.005
9. max.perm.body burden	μCi/g	0.01	...	0.002
10. limiting specific activity	μCi/g	0.01	70	0.002
11. world capacity at the limiting specific activity	Ci	2×10^{14}	1×10^{12}	1×10^{10}
12. annual replacement rate	Ci/year	1×10^{13}	7×10^{10}	1×10^{8}

Notes

*MPC stands for maximum permissible concentration.
**specific activities are in μCi per gram of stable element.

entitled? To what portion of this share is each nuclear undertaking entitled?

The United States constitutes about 7% of the world's surface and in 1966 had about 6% of the world's population. (6) On the other hand, the United States is at present using about 30% of the world's energy. (7) If the principle of one man, one vote is extended to one man, one polluter, the United States' allocation is about 6% of the world's capacity to accept radioactive wastes.

Nuclear explosives (fission and fusion) and nuclear power (fission) are today the dominant sources of the three radioisotopes considered in this paper. Whether an equal share of the available capacity is to be allotted to each of these undertakings, or whether more of the capacity goes to one than the other is a matter to be decided on the relative importance of explosions and power. As an illustration, but surely not as a recommendation, the following calculations have been made by allocating a half of the U.S. capacity to nuclear explosions, a half to nuclear power.

Table 3 summarizes the radiological and allocational considerations, and indicates that about 1/1000 of the replacement rates in the last row of Table 2 is appropriate for U.S. nuclear explosions, and an equal amount for U.S. nuclear power.

Table 3. Summary of considerations

	Factor
Radiological	
individual variation from the average	1/3
summing of doses from various isotopes	1/10
Allocation	
United States' share of world capacity	0.06
share allotted to nuclear explosions (an equal share is allotted to nuclear power)	1/2
combined factor	0.001

PRODUCTION OF THE THREE RADIOISOTOPES

The production of the three isotopes under consideration by nuclear explosions is a function of several factors: a) the fission to fusion ratio, b) the atomic composition of the explosive device and its associated equipment, c) the composition of any neutron shield that is used, and d) the composition of the soil in which the explosive is detonated. These factors may be manipulated for engineering purposes, and are, further, veiled by security classification. The estimates for the production of the three isotopes by nuclear explosives have been based on the declassified information in the upper portion of Table 4.

The corresponding production figures for tritium and krypton-85 are given in the lower portion of Table 4. Note that no figures for the production of carbon-14 by nuclear power appear in Table 4. Such production certainly occurs by neutron capture in nitrogen whenever air and neutrons get together, but no estimates of production rates appear to have been made.

amounts of tritium produced by these reactions in power reactors may perhaps equal the tritium produced by fission. (13) As a consequence, the tritium production figure in Table 4 should be increased from 14 to perhaps 30 Ci per electrical megawatt-year.

LIMITS ON NUCLEAR EXPLOSIVES AND NUCLEAR POWER

In Table 5 the production figures developed in Table 4 for tritium, krypton-85 and carbon-14 have been used to determine the limits imposed on nuclear explosives and nuclear power by 1/1000 of the world replacement rates, given in Table 2. It is evident from Table 5 that the limit on U.S. nuclear explosions is set by carbon-14 at about 70 megatons per year and that U.S. nuclear power is limited by krypton-85 to about 150,000 electrical megawatts.

DISCUSSION

Under the idealized conditions used in these calculations, 90% of the final equilib-

Table 4. Production rates of the three radioisotopes

Nuclear explosives	
fission to fusion ratio (8)	10 kt fission for 1 Mt fusion
10 kt of fission (9)	1.46×10^{24} fissions
krypton-85 fission yield (10)	2.93×10^{-3} per fission
krypton-85 production	290 Ci per 10 kt fission, i.e., per 1 Mt fusion
tritium production (8,9)	1×10^{7} Ci per Mt fusion
carbon-14 production (8)	15 Ci per Mt fusion
Nuclear power	
electrical to thermal ratio	1 Mw(e) for 3 Mw(t)
1 Mw(e) for 1 year (11)	9.86×10^{23} fissions
krypton-85 fission yield (10)	2.93×10^{-3} per fission
krypton-85 production	480 Ci per Mw(e) in 1 year
tritium fission yield (12)	9.5×10^{-5} per fission
tritium production	14 Ci per Mw(e) in 1 year

Tritium may be produced in nuclear reactors by neutron capture in hydrogen-2 and in lithium-6. It has been estimated that the specific activities will be reached in about three half-lives, say 35 years for tritium and krypton-85, and 20,000 years for carbon-14.

Table 5. Limits on nuclear explosions and nuclear power for the United States

	H-3	Kr-85	C-14
World annual replacement rate, Ci/year (from Table 2, row 12)	$1x10^{13}$	$7x10^{10}$	$1x10^{6}$
The United States' share for nuclear explosives, or power, Ci/year (see Table 3)	$1x10^{10}$	$7x10^{7}$	$1x10^{3}$
Limit imposed on nuclear explosives, Mt/year	1,000	240,000	67
Limit imposed on nuclear power, Mw(e)	$7x10^{8}$	150,000	...

It is possible to release more than the equilibrium rates in some years, but such overages must be compensated by releasing less than the equilibrium rates in other years. This is analogous to buying on credit and does not violate the Atomic Energy Commission requirement that exposures may be averaged over periods no longer than one year, provided the limiting specific activities are not exceeded. (2)

The premise that the three isotopes are released to the environment in periods shorter than their half-lives should be questioned. If it can be shown, or if it can be arranged that 90% of the limiting isotope can be restrained from entering the environment for three or more half-lives, the limiting rates in Table 5 may be increased by a factor of ten.

The premise that the three radioisotopes equilibrate throughout the environment in periods shorter than their half-lives is tenuous. However, to the extent that equilibrium is not established, specific activities will be higher in some locations than would be the case in complete equilibrium. If the portions of the environment that are at higher than equilibrium specific activities lie on human food pathways, then limits lower than those in Table 5 must be used.

The factors used to allow for individual variations from the average, for the summing of doses, and for rationing may be considered as conservative safety factors. Safety and conservatism receive great, perhaps undue emphasis in radiation. However, in considerations of the environment, it is wise to set aside certain portions to lie fallow for future and unforeseen needs.

The concept of balancing risks against benefits has been worked very hard, perhaps to exhaustion, in radiation protection. In the present context this concept leads to two questions of singular subtlety: risks to whom? benefits to whom?

CONCLUSIONS

The deliberations presented here lead to the conclusions that on the long view U.S. nuclear detonations are limited by carbon-14 to an average rate of 70 megatons per year, and that the corresponding limit for U.S. nuclear power appears to be set by krypton-85 at 150,000 electrical megawatts. These limits can be raised if means are devised to prevent the escape of the limiting radioisotopes to the environment.

The work reported here was performed under the auspices of the U.S. Atomic Energy Commission while the author was a summer visitor at the Lawrence Radiation Laboratory, Livermore, California.

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These premises lead to the conclusion that U.S. nuclear detonations are limited by carbon-14 to 70 megatons per

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G. Hoyt Whipple was born in San Francisco on May 4, 1917. He went to public schools in Rochester, New York and earned his bachelor's degree in Chemistry at Wesleyan University in 1939. From 1939 to 1947 he was at the Massachusetts Institute of Technology, first as a graduate student in physics, and then as a staff member in the Division of Industrial Cooperation, where he was involved with research and development concerning Loran, dehydrated food, and aerial bomb fuses. In 1947 he went to work for the General Electric Company in Richland, Washington, where he remained for three years as the leader of a small group concerned with special problems in radiation protection.

In 1950 he was offered the opportunity of completing his Ph.D. in biophysics at the University of Rochester and did so in 1953 with research which employed luminous bacteria to measure the relative biological effectiveness (RBE) of radiations from the 250 MeV University Cyclotron. He continued at the University of Rochester Atomic Energy Project for four more years as an assistant professor in radiation biology, teaching Atomic Energy Commission Health Physics Fellows, and conducting research in biophysics.

In 1957 he was offered a position of associate professor of radiological health in the School of Public Health, University of Michigan to develop graduate programs in radiological health. He was promoted to full professor a few years later and remains in this position today.

His publications concern biological effects of radiation, radiation safety in nuclear power plants, industrial radioactive waste disposal, environmental radioactivity, and education in radiation protection. At one time or another he has served as a consultant to the U.S. Air Force, the State Department on the Atoms for Peace Program, the U.S. Atomic Energy Commission, the International Atomic Energy Agency, and a number of industries in particular electric utilities.

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